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Lime treated soil as an erosion-resistant material for hydraulic earthen structures

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This paper deals with the recent research results obtained through SOTREDI research project, "SOil TREatment for DIkes" undertaken by the Lhoist Group, a lime producer, in collaboration with several research centers and universities. Lime-treatment of soils is a process that improves the workability of clayey materials and imparts them strong mechanical properties after compaction. These benefits are well-known and are used extensively worldwide for the construction of embankments for roads, highways, railways, industrial platforms... However, little is known about the way lime-treated soils behave in the context of hydraulic structures, where the properties of the materials vs water have to be determined.

In a first part of the project, it was demonstrated that lime-treated soils could reach permeability levels equivalent to those of untreated materials (i.e. 10^{-9} m/s to 10^{-10} m/s as measured in the laboratory) provided the right moisture content and compaction procedure were used.

Full-scale trials showed the feasibility of the procedure at the industrial level. Thanks to the use of modern technology - new mixing plant (stationary or mobile) and kneading compaction - offering a guarantee of homogeneity, adequate textural properties and conditions for placing the materials were obtained. Following this procedure, a real-scale dike was built in September 2011, to validate the applicability of lab results at full scale. In-situ and laboratory (on cored samples) mechanical and hydraulic measurements are in progress on this structure. This experimental embankment is the subject of a first companion paper by M. Froumentin et al. with the Centre d'Expérimentation et de Recherche (CER).

In a second part of the project, the effect of the lime-treatment against various failure mechanisms, in particular internal or external erosion, could be highlighted by a series of results:

- *the shrinkage limit of soils was shifted towards higher moisture contents, well above the optimum moisture content,*
- *the material becomes non-dispersive in the standard Crumb-test, even only 1 day after treatment*

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- *the critical shear stress for erosion is increased by one to two orders of magnitude in the Hole Erosion Test and Jet Erosion Test, strongly reducing the risk of piping. Details about these results are described in two other companion papers by S. Bonelli et al. (Irstea) and C. Chevalier et al. (Ifsttar).*

In parallel, the durability of lime-treatment can be observed after more than 30 years on the Friant-Kern irrigation canal in California, as described in a fourth companion paper by G. Herrier et al. Finally, the data described in this paper strongly suggest that lime-treated soils could be successfully used in the design of earthen hydraulic structures (namely canals, dams, dikes and levees).

Key words

lime treatment, piping, erosion resistance, permeability, durability, dike design

I INTRODUCTION

Lime treatment of soils is a technique widely used for soils improvement and stabilization for construction of roads, highways, railways, platforms. [Little, 1995; GTR French Guide, 2000] If the use of lime for transportation infrastructures is well-known, however the principles of lime treatment for hydraulic earthen structures remains barely applied or even forgotten, at least in Europe.

During the “TREMTP” Symposium (Treatment and REtreatment of Materials for Transportation Infrastructures” held in Paris in 2005, no paper was released about soils valorization for hydraulic earthen structures, and particularly lime treatment of silty or clayey soils. This was probably due to the general wisdom that a treatment of soils by lime induces a decrease of the dry density after compaction, and could bring a higher permeability of the obtained materials.

Nevertheless, lime has been used for five decades for improving and re-using the soils in levees, earth dams, flood dikes, mainly in US and Australia. The treatment of soil with lime was reported to solve erosion problems due to dispersive soils, to prevent shrinkage-swelling phenomenon coming from heavy plastic soils, and therefore stabilize the slopes. Even if the mechanical (cohesion, resistance...) and hydraulic (permeability, erosion resistance...) properties of those existing structures were not measured or reported, the solution of lime-treatment of soils appears to be efficient.

Those past experiences and the necessity to evaluate a series of unknown characteristics and relevant properties of lime-treated soils, led the Lhoist Group, a lime producer, to undertake in 2005 the ambitious SOTREDI research program : “SOil TREATment for DIkes”. The aim of the project was to investigate the benefits of lime treatment of soils, to measure and describe the relevant properties of these materials for an application in hydraulic context. The acquired knowledge from this project, achieved in partnership with recognized Research Institutes and Universities, is reported and interpreted in this paper.

II EXPERIMENTAL

II.1 Materials

The limes used for soil treatment studies were a calcic quicklime CL-90 Q (according to European Standard EN 459-1), with an available CaO content of 90.9 %, and a t_{60} (reactivity) of 3.3 minutes, and a hydrated lime (CL-90 S).

Six different fine soils with different Plasticity Indexes (PI), from silty (PI=8) to clayey (PI=37) have been used to perform the following tests: permeability, isotropic compression, oedometric compression, shrinkage-swell, crumb test, hole erosion test and MoJET (Mobile Jet) test.

II.2 Permeability

The construction of a hydraulic structure involves the control of its water permeability, that has to be the lowest possible to limit the water ingress through the bottom and the slopes. In the literature, few studies were concerned by permeability of lime-treated soils, and led to contradictory results. Moreover, preconceived idea is that permeability increases after lime treatment, due to the decrease of soil dry density. IFSTTAR (former LCPC) realized an experimental study on the influence of the procedure of lime treatment and compaction of a silty soil on its permeability. This silty soil, coming from Moulin de Laffaux, Aisne

department (France), had the following characteristics: clay fraction ($<2 \mu\text{m}$) = 23% ; silt fraction (between 2 and $50 \mu\text{m}$) = 59 % ; 88% particles $<80 \mu\text{m}$, $\text{PI}=12.7$, $w_{\text{OMC}}=15.8\%$, $\rho_d=1.81\text{g/cm}^3$.

Two different moisture contents have been applied at compaction: the first around the water content at the maximal density of Standard Proctor test (w_{OMC}), and the second, a humid state equivalent to 1.2 times above this value (w_h). Untreated material, 2 and 3% quicklime-treated, and 2.65% hydrated lime-treated materials were compacted according two procedures:

- classical Standard Proctor dynamic compaction, to 95% of the maximal dry density at OMC;
- kneading compaction, performed with a specific tool which simulates the action of a sheepfoot roller (Figure 1a) [Kouassi, 1998]. This tool allows respecting the following geometrical and surface characteristics given by a kneading compaction roller Caterpillar 825C:

- the surface ratio between a wheel and the compacted surface (ratio = 3.7),
- ratio between the thickness of a compacted layer and the foot height (ratio = 1.5).



Figure 1: Kneading compaction tool for laboratory tests (a) simulating the sheepfoot roller compaction (b), and permeameter (c).

The specimens were compacted to the same final density as that of the Standard Proctor method. In the case of untreated silt, this last compaction procedure led to similar optimal values (ρ_d and w), but for lime-treated materials, the kneading led to higher optimal water contents.

The permeability tests were performed at LRPC Angers (France), according to the XP CEN ISO/TS 17892-11 Standard. The samples were directly compacted in the permeameters (Figure 1c). When the kneading compaction was applied, the specific tool was pushed 8 times with a pressure equal to 1.25 MPa on the soil, with a gyratory movement. The specimen was obtained after the compaction of 3 layers of around 4 cm thickness each.

The permeameter set-up was similar to CBR moulds except that they were equipped with inox grids and pierced plates for the water entrance and exit. The permeability measurements were performed after 28 days curing at constant water content (after compaction), after 28 days curing + 2 months immersion period, and 28 days curing + 5 months immersion; in other words 3 months and 6 months after preparation, respectively. The following results were highlighted:

- kneading compaction led to the lowest permeability values (k) for a given mixture;
- for a given material with fixed compaction procedure, the humid state also gave lowest k values;
- the k values of lime-treated soils, Proctor-compacted in the humid state, lied between $5 \cdot 10^{-8}$ and 10^{-9} m/s;
- kneading compaction of lime-treated soils at high moisture content (humid state) led to k values below $5 \cdot 10^{-9}$ m/s, even below 10^{-10} m/s.

The k values remained constant with time, whatever the hydraulic loading application (constant or variable loading). This indicates that the final permeability was already obtained after 1 month (curing done with constant water content). As a result, the preferred conditions for reaching low permeability values of the lime-treated silty soil (2 to 3% lime) are: (i) high moisture content and (ii) kneading compaction. These results were further explained by mercury intrusion porosimetry which highlighted the changes in the poral structure of treated soils (Figure 2). The biggest pores ($>3\mu\text{m}$), and intermediate-sized (between 3000 \AA and $3\mu\text{m}$) are considered as responsible for the water path. When treated with lime, a third class of smaller pore appeared ($<3000 \text{ \AA}$). After lime-treatment in the humid state and kneading compaction, the amount of pores $> 3\mu\text{m}$ was strongly reduced in favour of the smallest pore size (Figure 2, blue curve), that do not affect the permeability. As a conclusion, the placement method of lime-treated materials is far more important than final density in the control of permeability [Cuisinier, 2011].

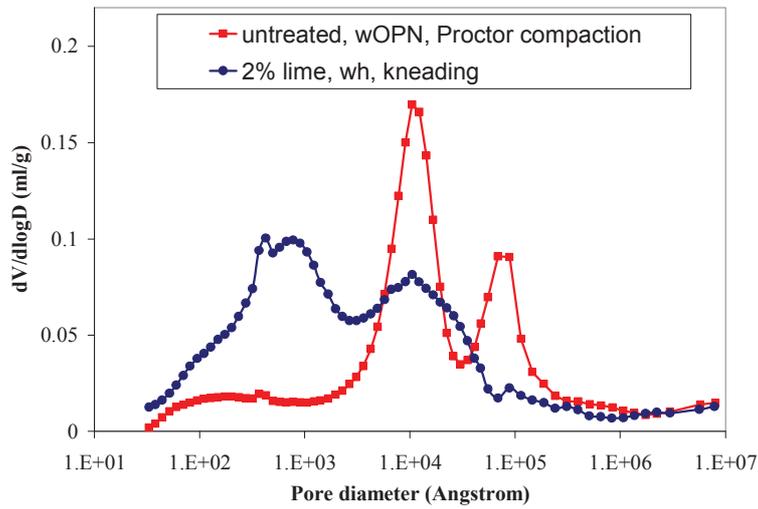


Figure 2: Mercury intrusion porosimetry of untreated (w_{OMC} , Proctor compaction: red curve) and lime-treated (high moisture content, kneading compaction: blue curve) samples, as a function of water content and compaction procedure (silty soil from Moulin de Laffaux, France, $PI=12.7$).

II.3 Mechanical behaviour of lime-treated soils

II.3.1 Compressibility

Isotropic compression tests were performed on the same silt as the one used for permeability (Figure 3). The volume strain of the untreated sample is function of the logarithm of isotropic stress ($\log p'$), which means that the yield strength is below the smallest applied stress. Once treated with 2% lime and after 6 months, 2 slopes can be distinguished on the graph, separated by the yield strength between 400 and 500 kPa.

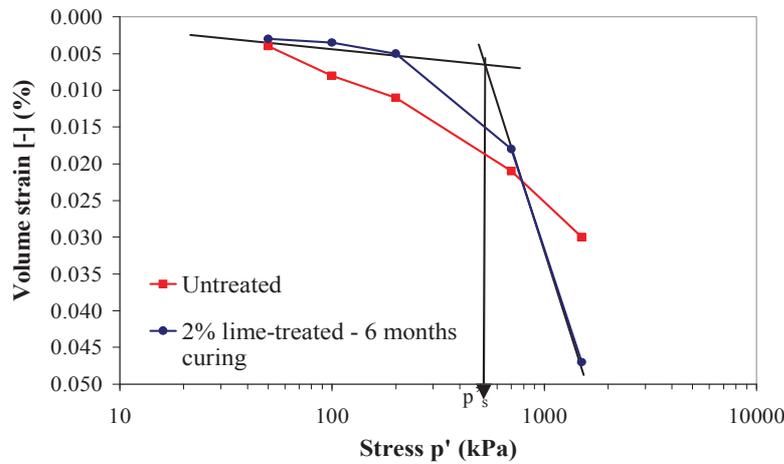


Figure 3: Isotropic compression of untreated and lime-treated silty soil from Moulin de Laffaux, $PI=12.7$ (6 month curing).

Oedometer tests were also performed at Université Libre de Bruxelles (ULB) on a clayey soil from Héricourt (Haute-Saône, France), untreated and 72 hours after a 5% quicklime treatment (dosage corresponding to the lime fixation point). This soil had the following characteristics: 94% particles $<80\mu m$, 75% $<2\mu m$, $w_p=35\%$, $w_L=72\%$, $PI=37$, $\rho_d=1.45g/cm^3$ at $w_{OMC}=27.5\%$. Several observations were made: the swelling index was divided by 5 to 10 times after treatment (C_s between 0.005 and 0.010), the yield resistance (p'_s) was also multiplied by a factor 5 to 10 (p'_s values between 490 and 660 kPa for the treated specimen). The compressibility indexes were similar for the two series.

II.3.2 Shear resistance

The aim of the shear resistance measurements is to quantify the improvement of mechanical stability of embankments brought by lime treatment. The results were obtained at ULB, on two silty soils from Belgium (Soumagne soil, $PI=16$ and Marche-les-Dames soil, $PI=11$), treated with 3% quicklime [Verbrugge, 2011]. Consolidated undrained triaxial tests were performed on samples of 3.6 cm diameter and 7.2 cm height,

beforehand saturated. The untreated first silt (Soumagne soil) parameters are $c' = 5.8$ kPa and $\phi' = 37.4^\circ$. The values obtained after treatment and at several curing times are reported on the Figure 4. The friction angle stays stable with time, whereas the cohesion rises significantly: after 2 years, the c' value is multiplied by 25. Similar results were obtained with the silt from Marche-les-Dames (PI=11), which shows a c' value equal to 500 kPa at 450 days after treatment. The range of measured cohesion values was well above common stresses met on small hydraulic structures.

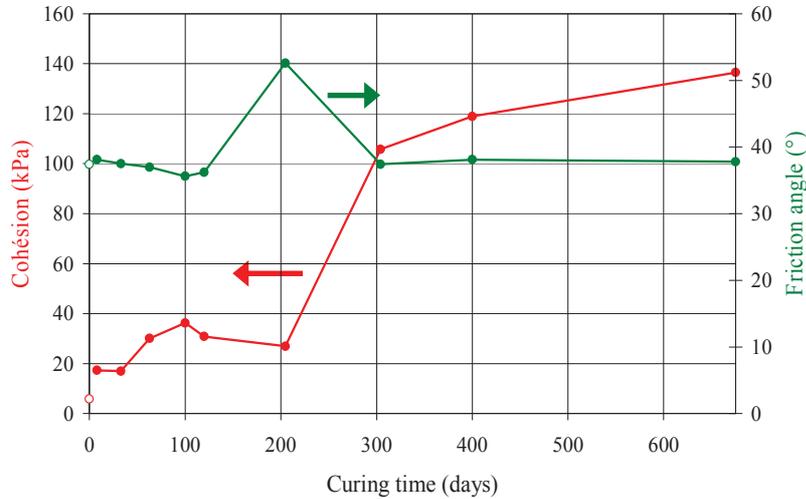


Figure 4: Evolution of the shear resistance parameters with time (treated silty soil from Soumagne, Belgium, PI=16). The white points at $t=0$ are related to the untreated specimen.

II.3.3 Interpretation of mechanical tests

The lime-treated soil can be considered as “cemented” material, in this sense that the particles assembly is realized by the cohesive bonds induced by the lime action. This new assembly has also a new stress resistance threshold; above this value, the assembly is destroyed and the behaviour of the material becomes similar to an untreated soil. For isotropic and oedometric compressive tests, this threshold is not considered as a preconsolidation stress, but more as the yield strength of the new lime-treated material of low ductility, quantifying the resistance of the adhesive bounds created by the lime treatment. The rise in cohesion is also due to the so-called pozzolanic reactions between lime, dissolved silica and alumina species from clays and water, giving a material that is almost not compressible, and not subjected to deformations if submitted to stresses until several hundred kPa.

II.4 Water sensitivity and erosion resistance

II.4.1 Dispersivity, swelling and shrinkage

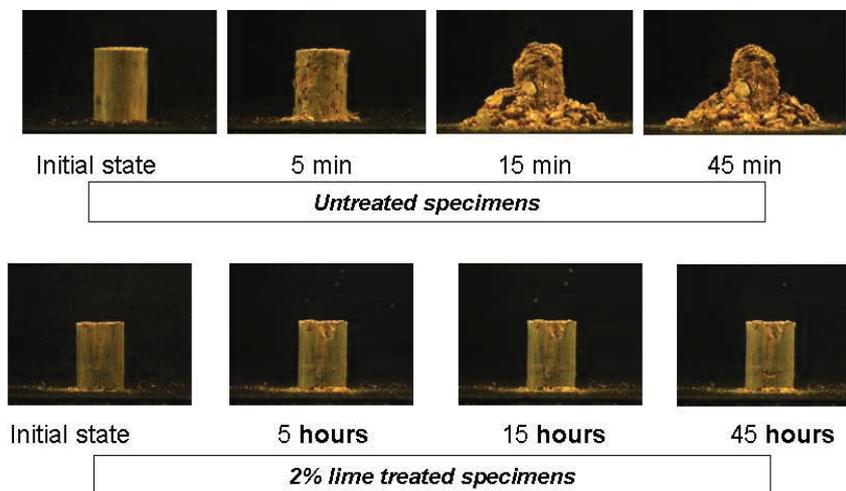


Figure 5: Enhanced crumb-test performed on the silty soil from Héricourt (PI=11), untreated (above, scale in minutes), and treated with 2% lime (below, scale in hours).

The ASTM D 6572-06 Standard (“crumb-test”) was used to demonstrate the non-dispersive behaviour of an initially dispersive silty soil from Marche-les-Dames (94% particles $<80\mu\text{m}$, $\text{PI}=11$), treated with 2 to 3% quicklime. This improvement was still visible 3 years after treatment. An enhanced crumb-test was also performed by IFSTTAR (France) [Chevalier, 2011; Pham, 2008]. A thin wall sampler was used to cut out specimens from moulded cylinders (Héricourt silty soil, 67% particles $<80\mu\text{m}$, $\text{PI}=11$ untreated and treated with 2% lime). The untreated cylinder collapsed after 15 minutes immersion, whereas no degradation occurs on the lime-treated sample, even after 45 hours immersion (Figure 5)

The consistency changes of clayey soils with moisture content are materialized by large volume changes (swelling and shrinkage). Laboratory tests on the Héricourt clayey soil (see Table 1 and 2.3.1.) showed that, after a 5% quicklime treatment, linear swelling of soaked CBR samples remained low and limited after the soaking step. In the mean time, the bearing capacity reached a value of 19, to be compared to the very low value of 1.3 obtained for the untreated sample.

Free shrinkage evaluation was also performed on this clayey soil according the German Standard DIN 18122-2. The principle consists in preparing a disc of soil (diameter 7cm, height 1cm) at very high water content (110 %), and measuring its diameter vs water content when left to dry at room temperature. The shrinkage limit w_s is the inflexion point of the two tangents to the volume variation curve (Figure 6). At this water content, the shrinkage of the sample reaches the maximum amplitude; below w_s , no volume variation is recorded. In other words, shrinkage/swelling risk exists for a soil if its water content is above w_s . Once again, natural Héricourt clayey soil was tested and showed a w_s of 16,5%, linked with a big volume variation (more than 50% shrinkage). Once treated with 5% quicklime, w_s is displaced towards higher water content ($w_s=55\%$), well above the OMC conditions, ensuring the volume stability of the material.

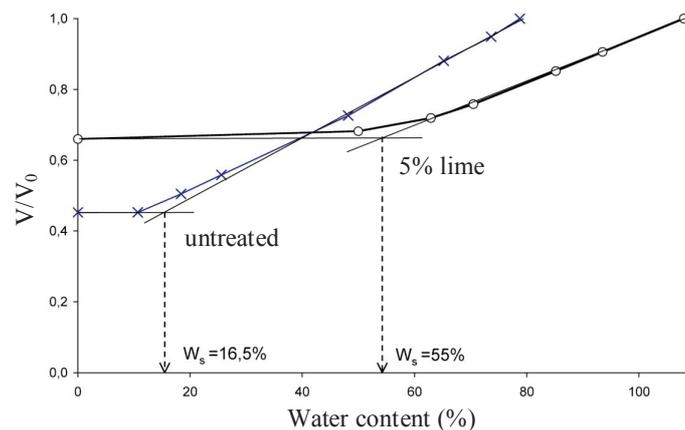


Figure 6: Free shrinkage curves of Héricourt clayey soil ($\text{PI}=37$).

II.4.2 Erosion resistance

Both internal (by Hole Erosion Test HET) and external (by Mobile Jets Erosion Test, MoJET) erosion resistance were studied, in order to evaluate the impact of lime treatment on the critical parameters of the materials. HET was performed at Irstea (France) on a clayey silt taken from a Camargue Dike (France): 95% particles $<80\mu\text{m}$, 30% $<2\mu\text{m}$, $\text{PI}=11$.

After lime treatment and 14 days curing, the critical stress was increased by a factor 20, and the erosion coefficient divided by 10. The device didn't allow the erosion initiation of the 28 days cured samples. HET results can be used to estimate the threshold water velocity that induces erosion (Figure 7). For untreated clayey silt, the erosion threshold corresponds to a water velocity of 2 m/s, whereas for lime-treated material, the value rises up to 10 m/s. These results are important elements for the problematic of internal erosion, main origin of hydraulic earthworks failures [Benahmed., to be published; Bonelli, 2011].

The surface erosion was also tested by the mean of MoJET test, performed at IFSTTAR. The procedure consists to spray 6 rotating water jets perpendicular to a sample surface, with a water flow of 600 ml/min, to recover the eroded particles and weight their dry mass. On a sample of Héricourt silty soil (67% particles $<80\mu\text{m}$, $\text{PI}=11$) treated with 2% lime and cured 90 days, the erosion could not be initiated, even with an increase of water flow to 2 l/min, when the same conditions gave 500 g of dry particles eroded from the untreated soil.

Experimental studies on erosion resistance of lime-treated soils are also developed in papers presented during ICSE-6 conference, by C. Chevalier and al., and S. Bonelli and al.

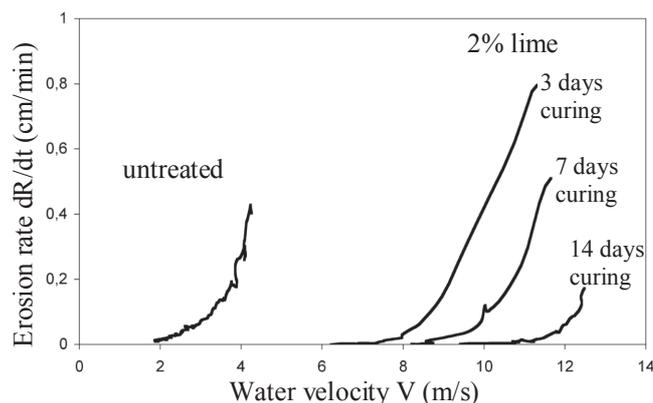


Figure 7: Hole Erosion Test: erosion rate vs water velocity for untreated and 2% lime-treated clayey silt from a Camargue dike (PI= 11).

III PAST AND PRESENT APPLICATIONS

Existing structures in USA are testimonials that prove the effectiveness and durability of the lime treatment solution for hydraulic applications. It is reported that two different problematic soil types have been involved:

- highly plastic, expansive clayey soils, that are concerned by volume changes, water ingress through the cracks and slope sliding ;
- less plastic silty clays, also called dispersive soils : less cohesive, they are more subject to erosion.

The Friant-Kern irrigation canal in California, restored in the 70's with lime-treated plastic soils, has been probably the best testimonial for the relevance and efficiency of soils lime treatment for a hydraulic use. This case is the subject of a companion paper presented during ICSE-6 conference by G. Herrier and al..

More recently, the Mississippi River dikes network from Ashton to Gale is an example of present uses of lime treatment for restoration or reinforcement. Several techniques are considered using lime [Lowe, 2010; US Army Corps of Engineers, 2010] :

- excavating the entire levee embankment, lime treatment and backfilling of these materials and compacting in place;
- excavate the upper levee embankment down a minimum of 2m, mixing it with lime, backfilling of these materials and compacting in place;
- use of injection of a lime/fly ash slurry into the levee side slope. Note that the issue of fly ash ecotoxicity and composition is still debated.

On the New Orleans dikes network, it has been decided to rise up the height of the dikes after Katrina storm [Grissett, 2010; Spaht, 2010]. The design takes into account the mechanical improvement brought by lime addition, because the dike height is raised by 4 m without changing the base width of the dike, thanks to a steeper slope.

IV POTENTIAL APPLICATIONS FOR HYDRAULIC STRUCTURES, FUTURE PROSPECTS

IV.1 Materials

The results acquired during the SOTREDI research program indicate that through lime treatment, the properties and behaviour of the resulting materials can meet 3 key factors insuring the construction, design, durability and limited maintenance of a hydraulic earthen structure: low permeability, mechanical and volume stability, internal and external erosion resistance.

The homogeneity of the treated soil is an issue in order to limit permeability gradients that can be the origin of abnormal local flows. Moreover, the difficulty to obtain a homogeneous material in Civil Engineering works is a permanent issue. The way the lime treatment was performed in the past, with treatment methods and devices that did not follow the current recommendations (i.e. kneading compaction of

a plant-treated soil in the humid state) gave nevertheless materials with good performance and durability. The use of a mobile plant showed the feasibility of the recommended procedure at industrial scale, and that it allowed for a precise control of lime content, moisture content (by controlled water addition), fineness and homogeneity of the treated soil. Feasibility of this method was demonstrated in September 2011 during a full-scale dry dike construction in CER (Rouen, France), using a low-plasticity silty soil treated with 2.5 % quicklime. This is developed in a companion paper proposed by I. Charles and al.

IV.2 Potential uses

Thanks to the mechanical improvement, erosion resistance and permeability levels conferred by a lime treatment using the specific conditions described in this paper, it is possible to foresee future uses in a lot of diverse hydraulic applications:

- reuse of heavy clays in dike or dam foundation, thanks to the absence of differential settlement, creep and the stability;
- homogeneous embankments in lime-treated soils for warm and dry countries, thanks to the reduction of shrinkage cracks, the improved workability and easier compaction procedures;
- construction of erosion-resistant external parts of hydraulic structures (blankets of levees,...)

V CONCLUSIONS

Lime treatment of soils was applied from the 70's, mainly in US, in hydraulic structures restoration and construction. It seems that this technique was forgotten in Europe. The design of canals, levees and dams can only be done with the proper knowledge of the adequate properties of lime-treated soils and their evolution. This paper described the corresponding results obtained in a research program launched by Lhoist in partnership with Universities and Research Institutes (Irstea, IFSTTAR, LRPC Angers, CER Rouen, Université Libre de Bruxelles). A series of relevant mechanical, stability, permeability and erosion-resistance properties of lime-treated soils was measured, which allows the development and the control of this technique, according to a specific method of treatment and compaction. This methodology has been applied for the construction of a real-scale lime-treated embankment; measurements of mechanical and hydraulic properties are in progress on this structure.

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